

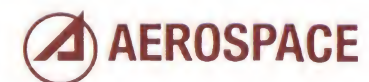


Lift-Off Acoustics Prediction of Clustered Rocket Engines in the Near Field

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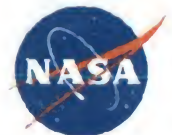
Spacecraft and Launch Vehicle Dynamic Environments Workshop
June 8-10, 2010, El Segundo, CA



Outline



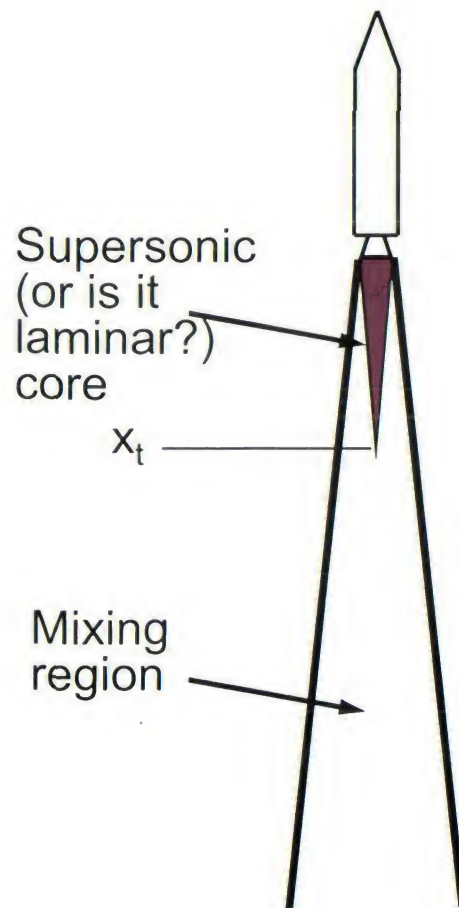
- Launch Environment
- Near Field
- Deflector, Shielding
- PAD Updates
 - *Directivity*
 - *Water Suppression*
 - *Clustered Nozzles*
- Summary



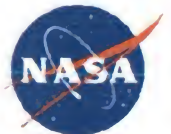
Launch Acoustic Environment

- Clustered rocket engines
- Ground reflections
- Near-field OASPL levels are high (160-170 dB)
 - *Water injection provides up to 10 dB reduction*
 - *Exhaust ducts can reduce SPL to some extent*
- Remember that slides are visual aids — not a document
 - *Supply handouts to audience with more information*
- Near-field produces random vibroacoustic impact
 - *Vehicle*
 - *Payload*
 - *Ground support equipment*
- Accurate near-field acoustic description is critical
 - *Next generation launch vehicles*

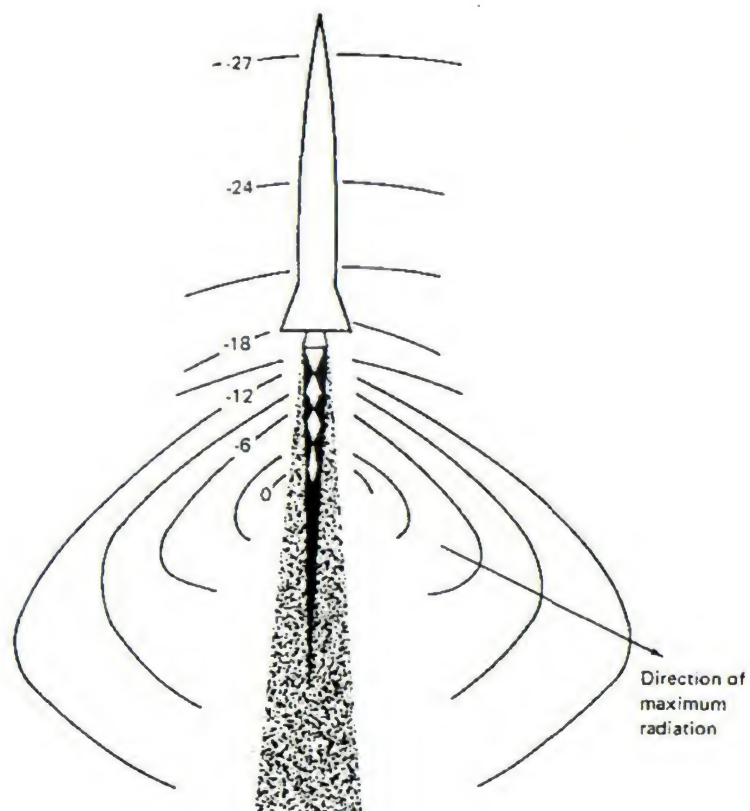
Rocket Noise Generation



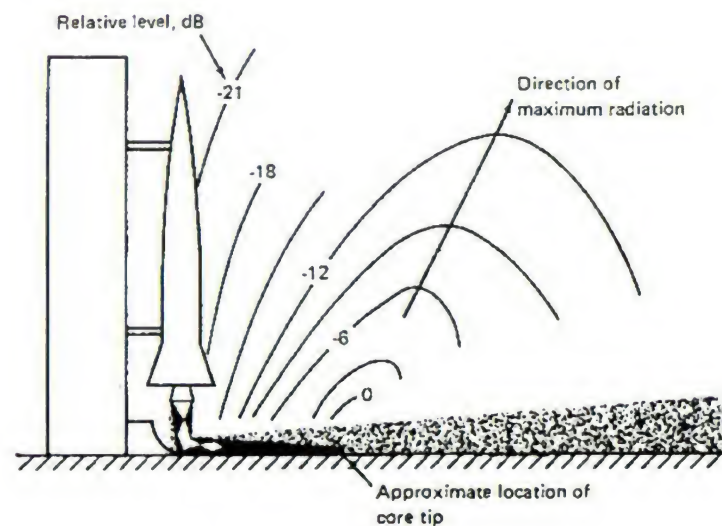
- Scales with nozzle diameter D_e , core length x_t , exit velocity V_e , thrust
- Distributed sources along axis
- Directivity
- Spectrum
- Far field: single directivity and spectrum
- Near field: spectrum and directivity vary along x
 - Scale with x/x_t , S_n
 - S_n based on D_e or x



Lift-off vs. Free-Flight Environment



Free flight



Lift-off



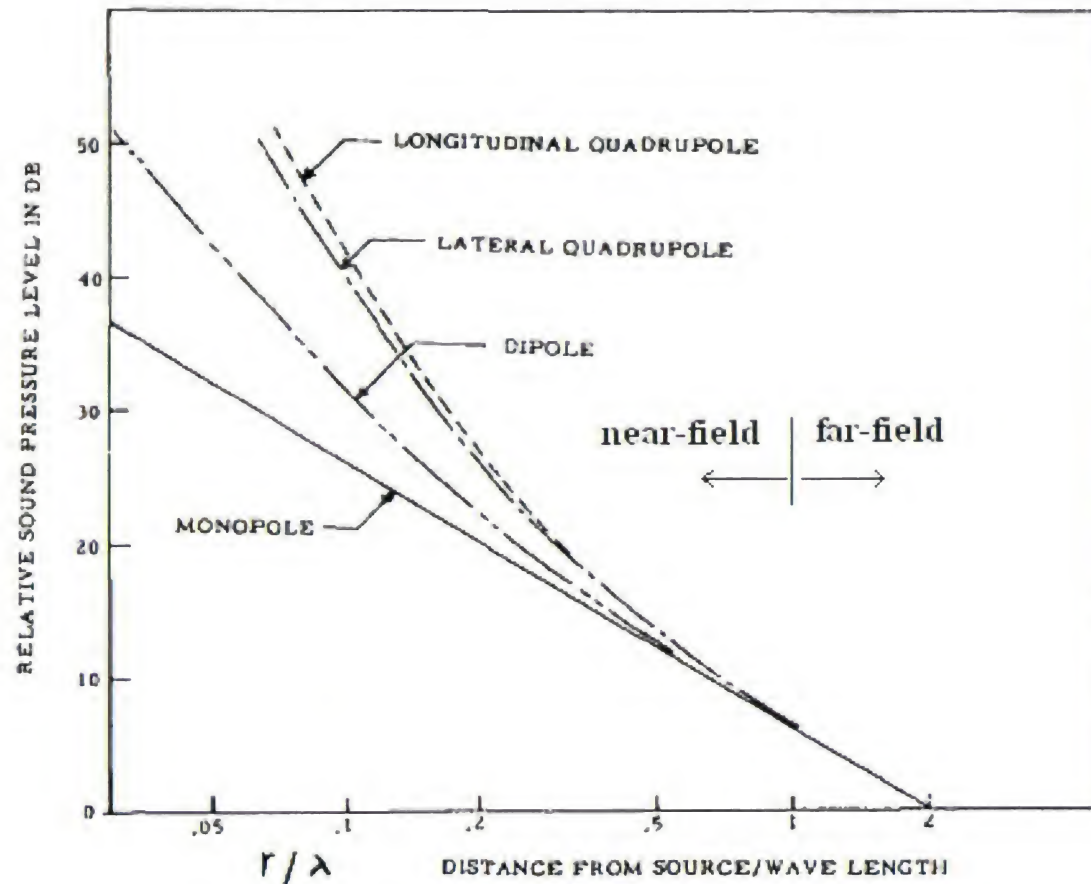
Near-Field Jet Acoustics



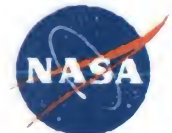
- Near-field definition: typically within 40 jet diameters (~300 ft for modern rockets)
- Near-field jet noise is complex relative to far field
- Noise generation and radiation
 - *Spatial source distribution*
 - *Hydrodynamic effects in addition to acoustic disturbance*
 - Nonlinearity
 - Convection, turbulence, jet interaction, shock waves
 - *High frequency*
 - *Refraction of sound*
- Ground and vehicle reflections
- Launch vehicle drift
- Water sound suppression



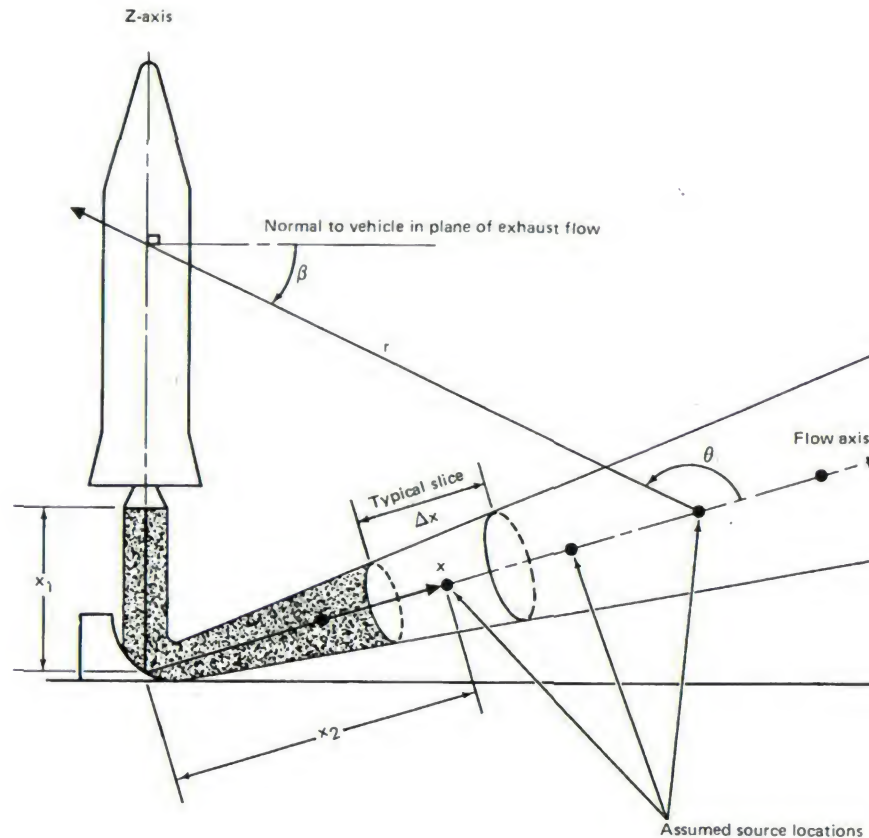
Near-Field Character of Isolated Sound Sources



Ref: Morgan, Sutherland, and Young, WADD-TR-61-178, 1961

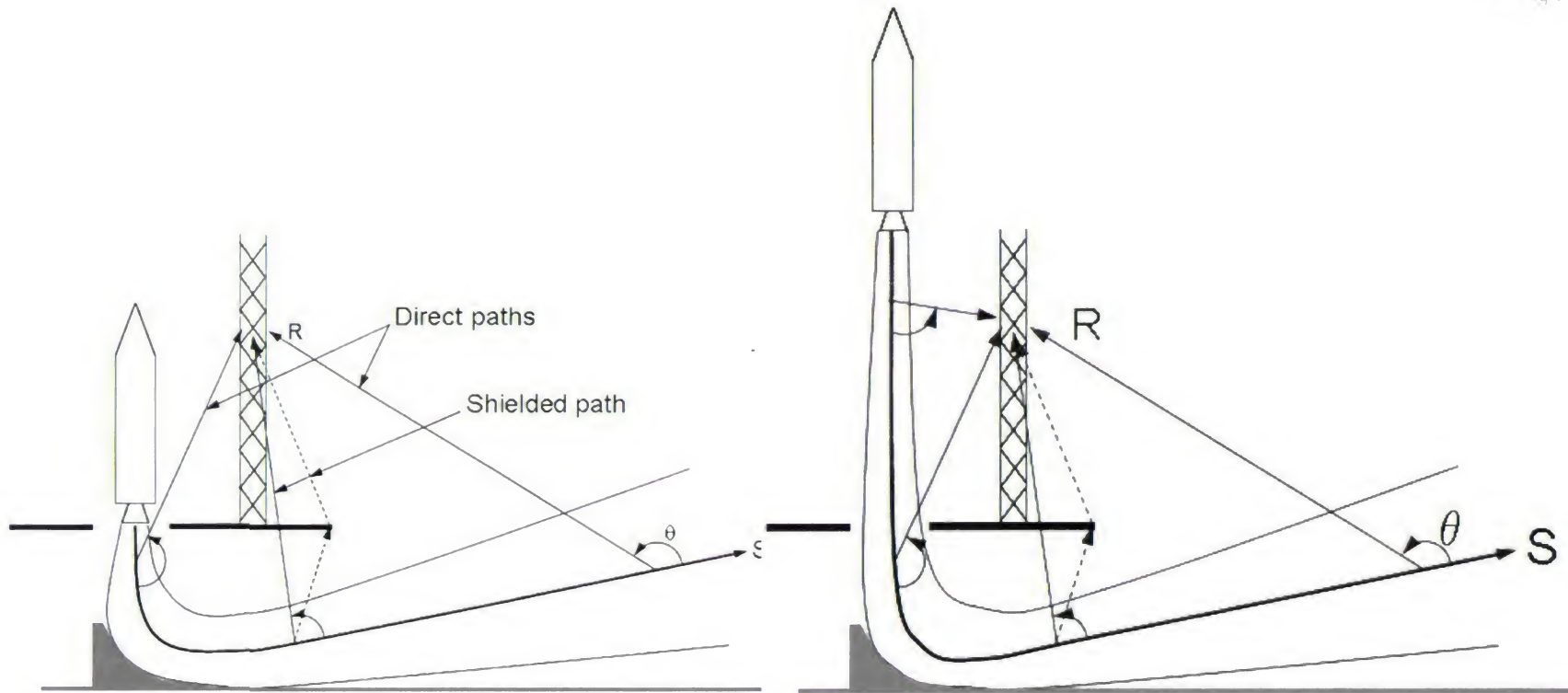


Rocket on Launch Pad



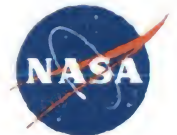
- Figure from SP-8072
- Deflector turns flow
- Deflector may change flow properties
- Near field, need distributed source
- Launcher deck or deflector tunnel blocks noise

Rocket on Mobile Launcher

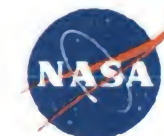
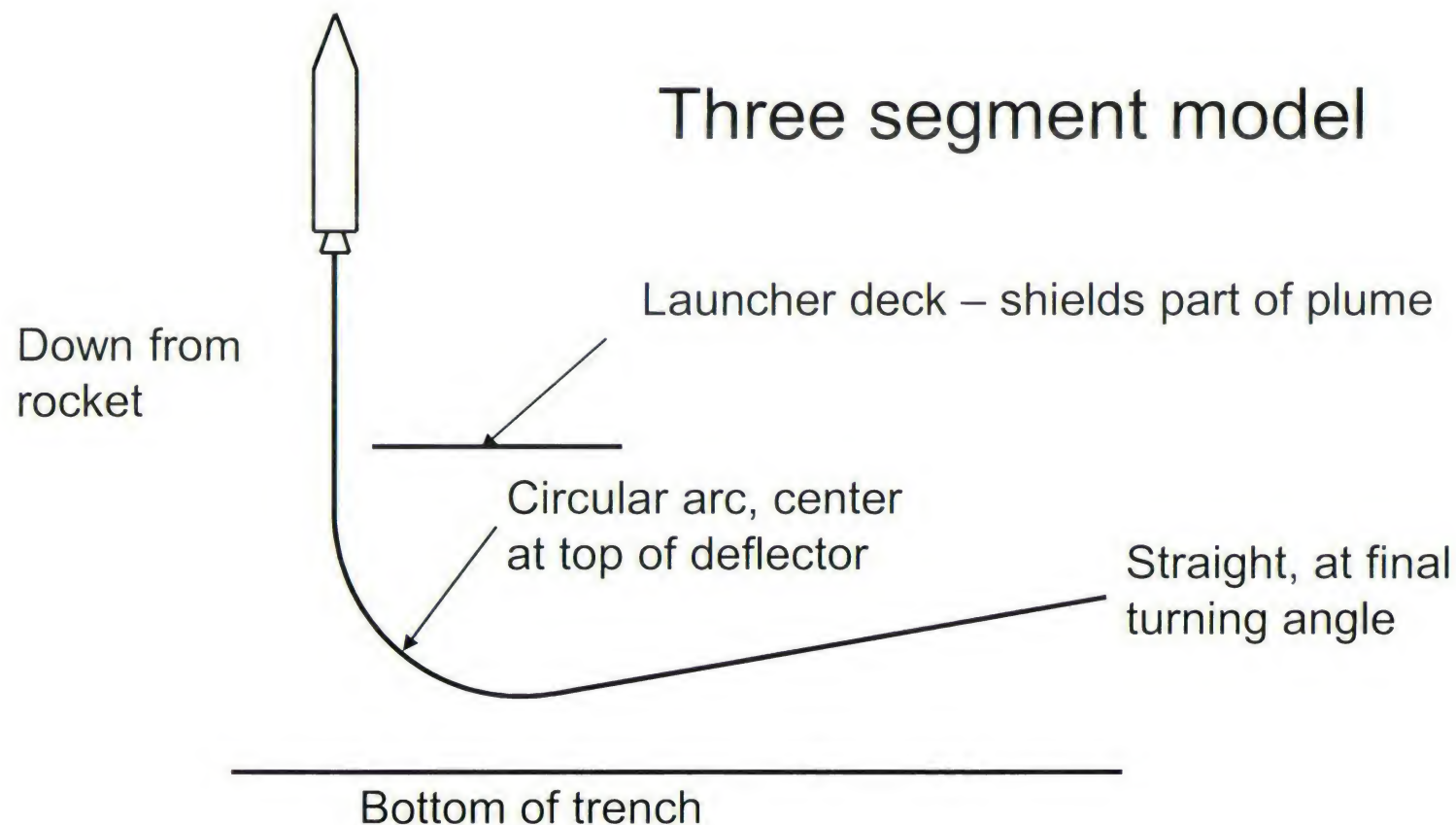


On pad, before lift-off

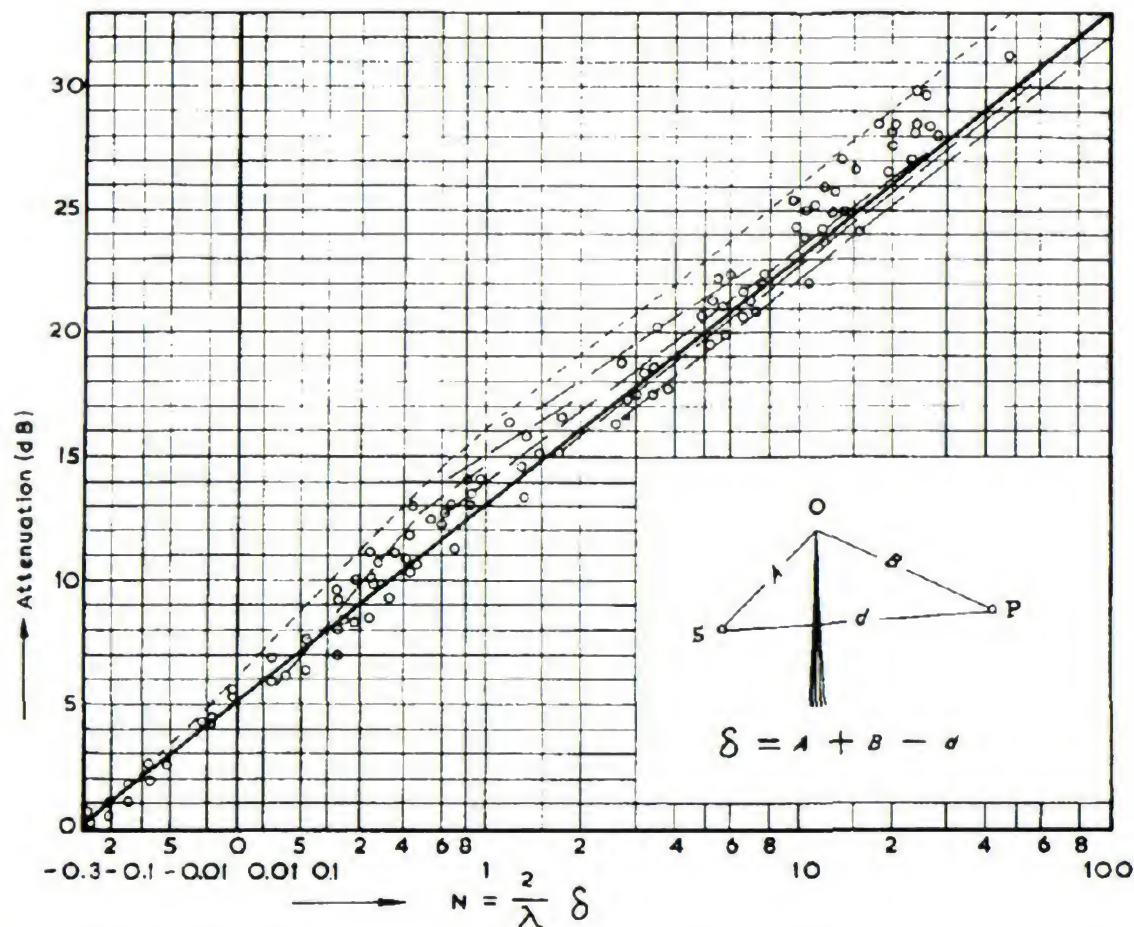
Above pad, after lift-off



Modeling Deflected Plume Axis



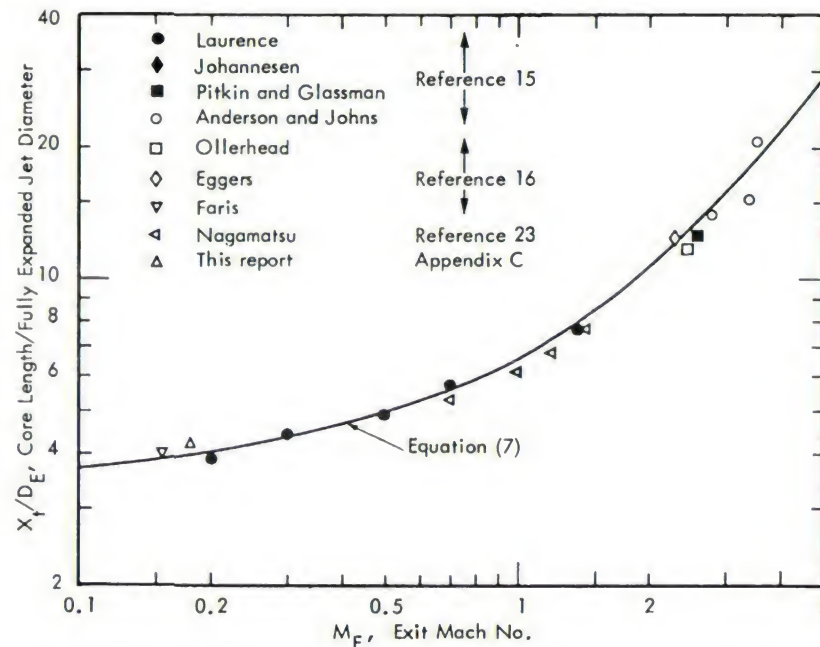
Acoustic Shielding



Ref: *Noise Reduction by Screens*, Z. Maekawa, *Applied Acoustics*, 1968, pp.157-163



Core Length



Ref: Eldred (SP-8072)

$$\frac{x_t}{d_e} = 3.45(1 + 0.38M_e)^2$$

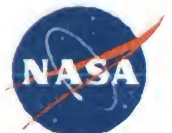
Other literature at variance with 8072 core length:

- Shirie and Seubold, 1967
- Varnier et al 1998 – nominally 40% of 8072 for SRM
- Recent fits by Jared Haynes supports Varnier
- Consistent with Laufer et al, 1976

PAD Code Development



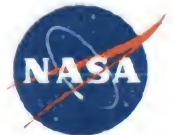
- Predict Ares-I launch noise levels and spectra at about 50 locations on launcher
- Use classic methods: WR 68-2, SP-8072, updated as necessary
- 2007 Effort: no suppression, vertical lift
- 2008 Effort: water suppression, drift
- 2010 Effort: two-zone method



Required Components



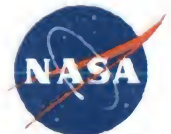
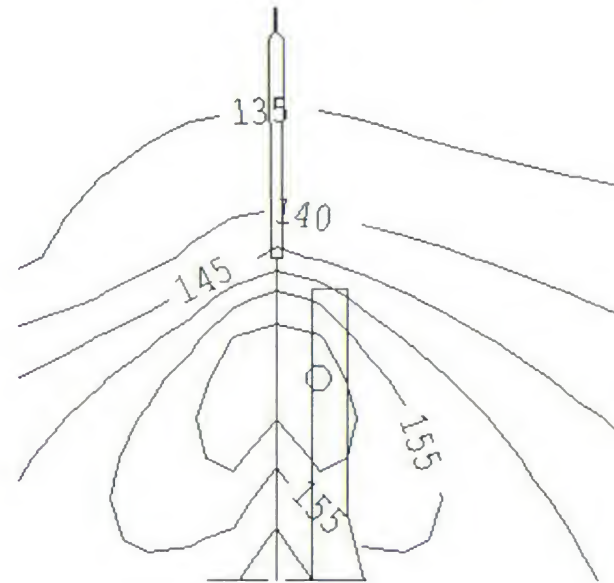
- Total sound power level of rocket
 - *Sutherland, 1993-1996*
 - *Consistent with Lighthill's theory*
- Distribution of source along x
- Spectrum – depends on x , S_n
- Directivity – function of x , f , S_n
- Effect of deflector



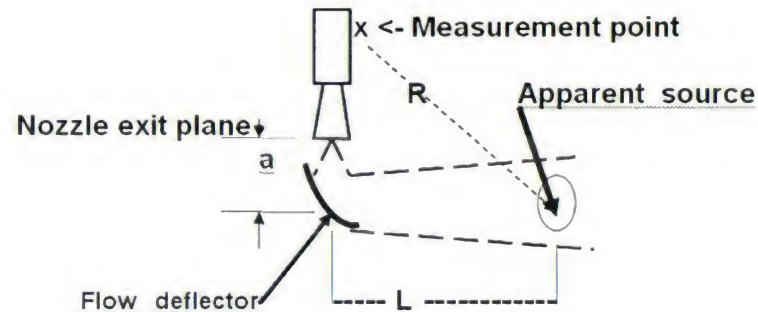
PAD Implementation



- Computes spectra in vicinity of launch pad, using the components described thus far
- Outputs at specific points or on a grid
- Fortran code, input/outputs are simple ASCII files
- Companion graphical display program.
- Xt multiplier (xtscale) scales Eldred core length

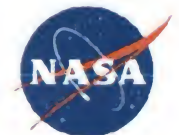


Source Spectrum

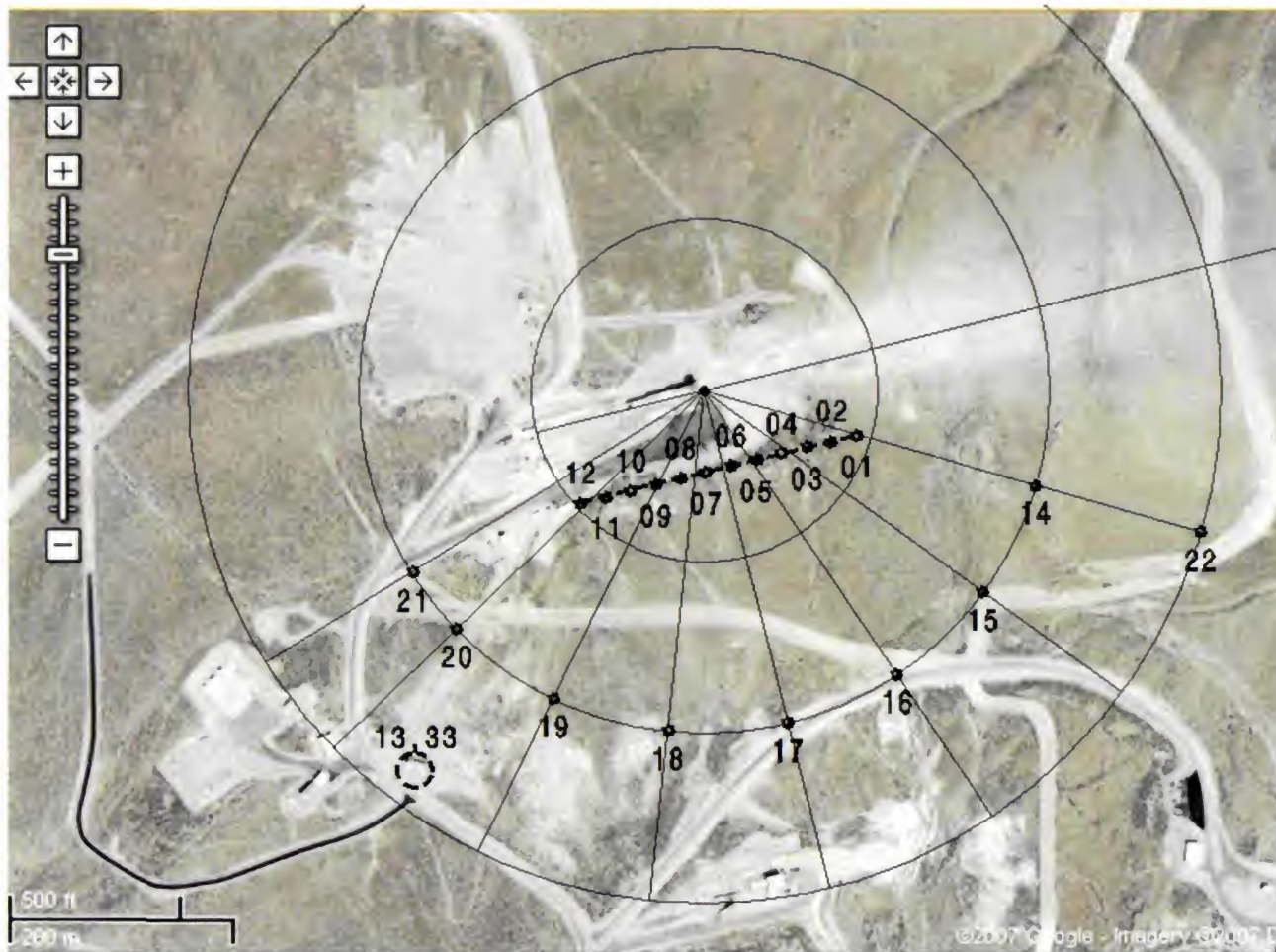


- Full method in PAD
- Spectrum at each x , per axial S_n fit
- Directivity per new DI fit

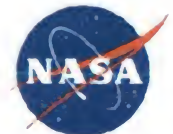
- Older “Dyer” or “Franken” method
- Single dominant frequency at each axial distance
- Amenable to empirical fit from actual rocket firings



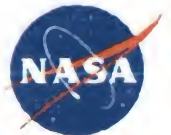
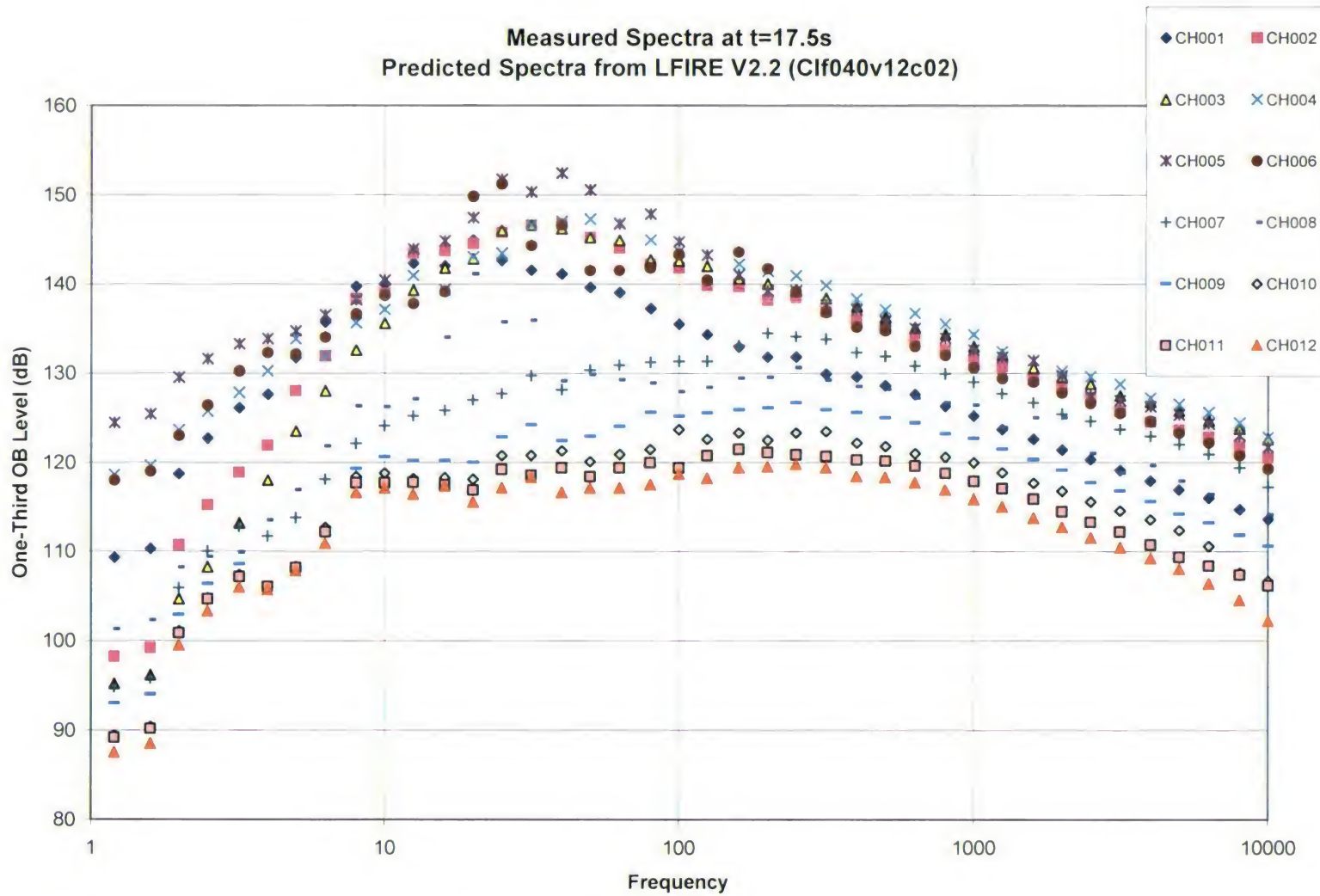
Data Validation



TEM-13 Measurements 1 Nov 07



Data Validation (cont.)



Suppression of Rocket Noise with Water Injection



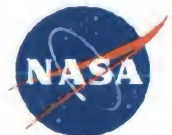
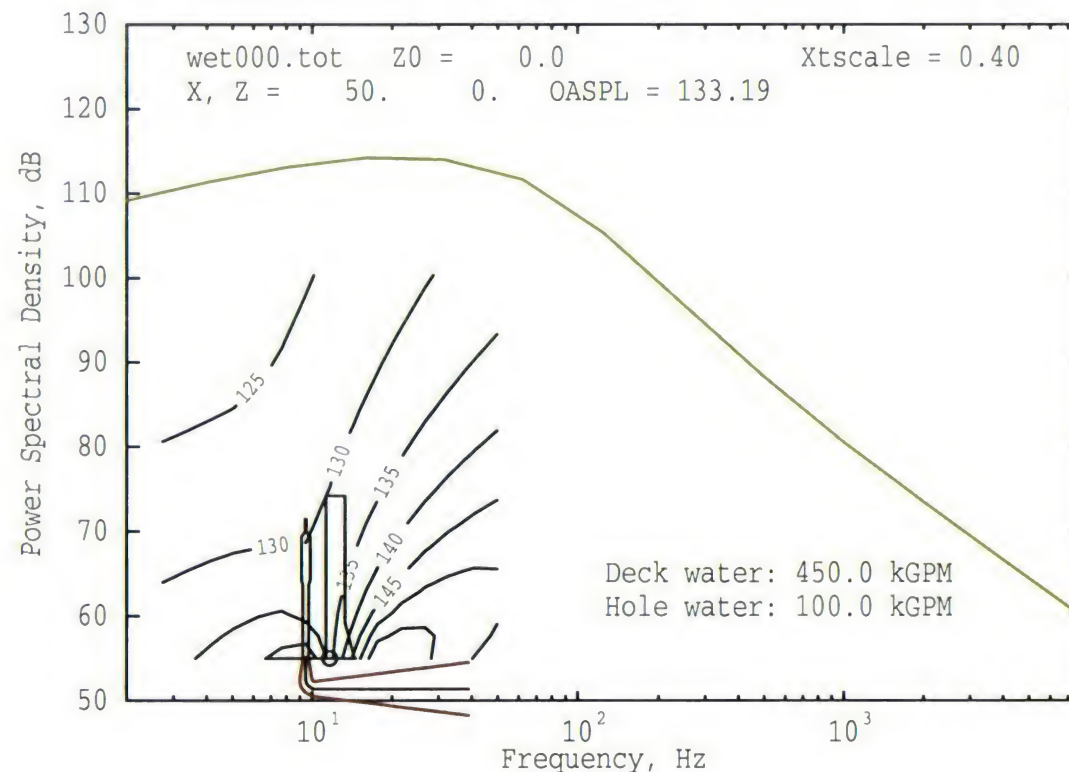
- Data from Full Scale and Model Tests
- Extensive Data on Change in Acoustic Efficiency with Water Injection
- Limited Data on Octave Band Levels in Near Field with Water Injection
- Basic Variable is Ratio, R_{mf} of Mass Flow Rate of Water to Rocket Exhaust
- Reasonable validation of water injection effect based on acoustic efficiency vs. ratio of water to rocket mass flow rate
- Scale model tests recommended for any new configuration
- Further evaluation of theory and detailed water injection methods, water nozzle shape, etc, may be desirable



Water Suppression Implementation



- Simple method: OASPL goes down per regression, proportional to R_{mf}
- Complex details:
 - *Effect of location and distribution of water injectors*
 - *Effect on distribution of noise sources within the exhaust*
 - *Addressed up to the limit of credible models*



Launch Drift

- Flat plate deflection
 - *PAD assumed exhaust always went through hole, never impinged on launcher deck*
 - *Need to adapt flat plate deflector data for partial impingement*
- 3-D geometry for shielding
 - *PAD uses simplified geometry, exploiting everything in one plane for current non-drift cases*

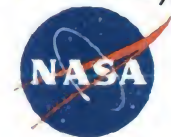
Clustered Rocket Engines



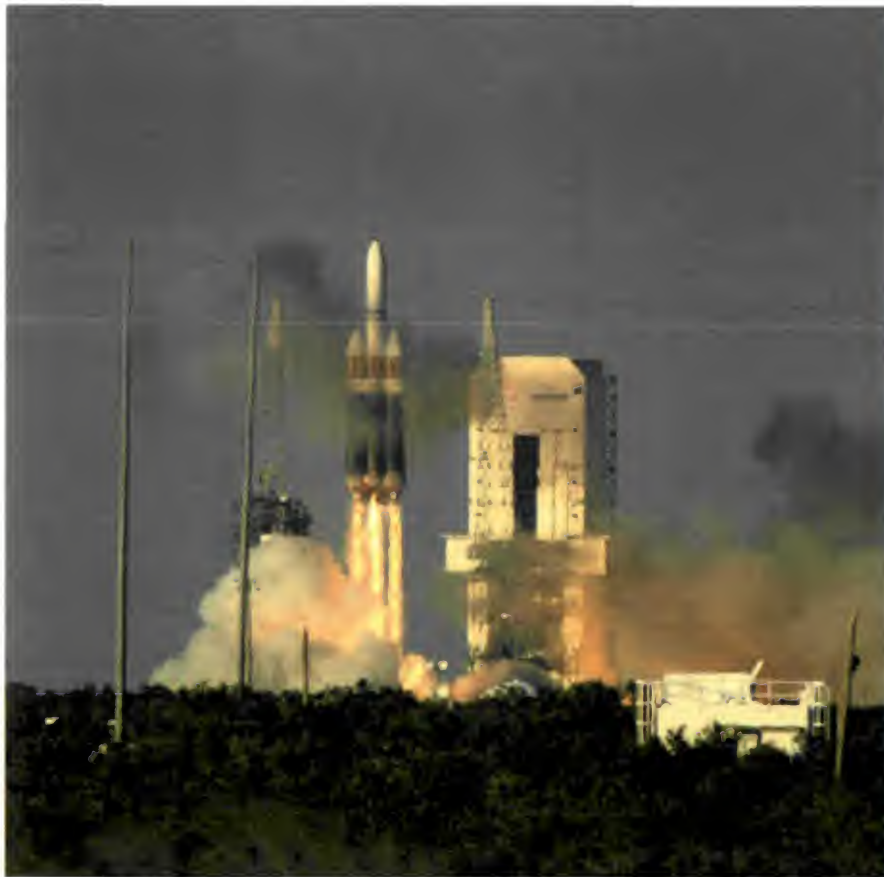
Space Shuttle



CFD (Ref: Slotnick, Kandula & Buning, AIAA-94-1860)



Clustered Rocket Engines (cont.)



Delta IV



Falcon 9



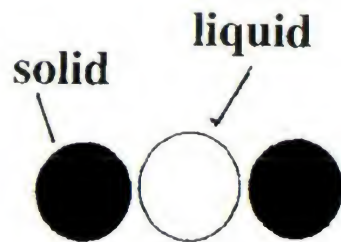
Clustered Rocket Engines (cont.)



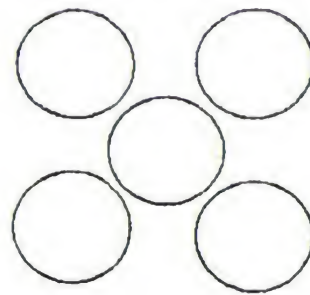
Taurus II



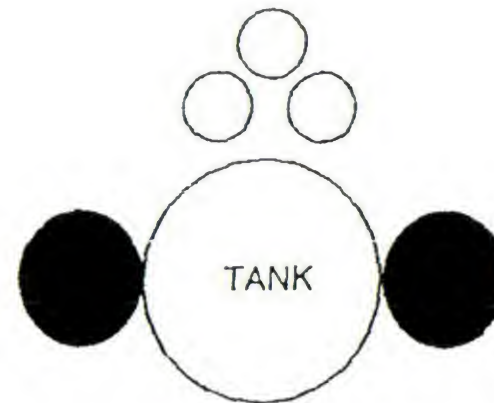
Familiar Cluster Configurations



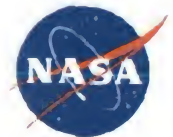
Titan



Saturn V



Space Shuttle



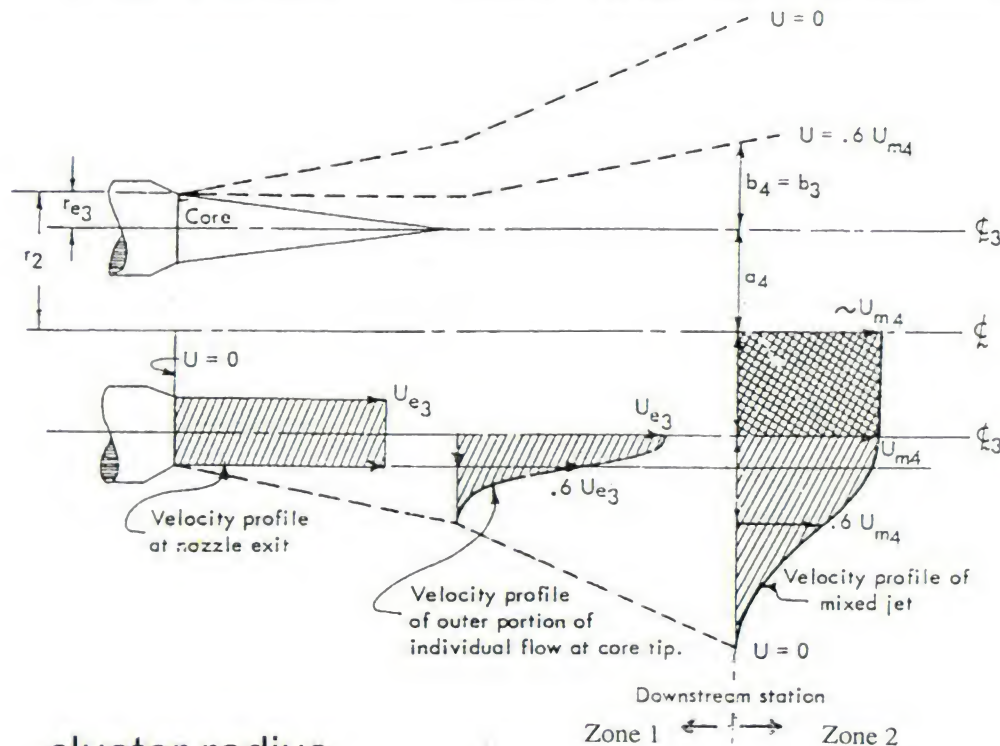
Classification of Clustered Nozzles

- Nozzle Spacing
 - *Widely spaced (clustered)*
 - Isolated nozzles (superposition)
 - Single peak frequency
 - *Closely spaced*
 - Single effective nozzle (total equivalent thrust)
 - Single peak frequency
 - *Intermediate spacing*
 - Two zones (isolated zone/mixed zone)
 - Double peak in frequency spectrum
- Homogeneous vs. heterogeneous clusters

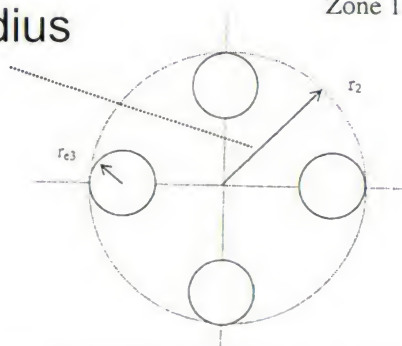
Methods for Clustered Nozzles

- Single zone NASA SP-8072 method (Eldred 1971)
 - *Applicable for isolated nozzles or tightly spaced nozzles*
 - Assumes single effective nozzle diameter ($d_e = \sqrt{n} d$)
 - Based on rocket noise data (wide thrust level range): spectral similarity, directivity
 - *Unsuitable for intermediate cluster spacing*
- Two-Zone methods for intermediate cluster spacing
 - *Eldred's model (1963)*
 - *Employ NASA-SP method for*
 - Isolated nozzle zone
 - Mixed zone
 - *Combine the two flows*

Eldred's Model



cluster radius



$$\frac{x_4}{x_i} = \begin{cases} \frac{2(r_2/r_{e3} - 1)}{n^{1/2} - 1} & x_4 > x_i \\ \frac{(r_2/r_{e3} - 1)}{n^{1/2} - 1} & x_4 \leq x_i \end{cases}$$

where x_i = core length

x_4 = length of mixing region

r_2 = radius of the cluster periphery

r_{e3} = radius of the individual nozzle

- Jet entrainment
- Mass, momentum & energy conservation



Properties of Combined Stream



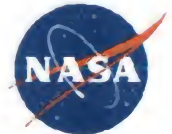
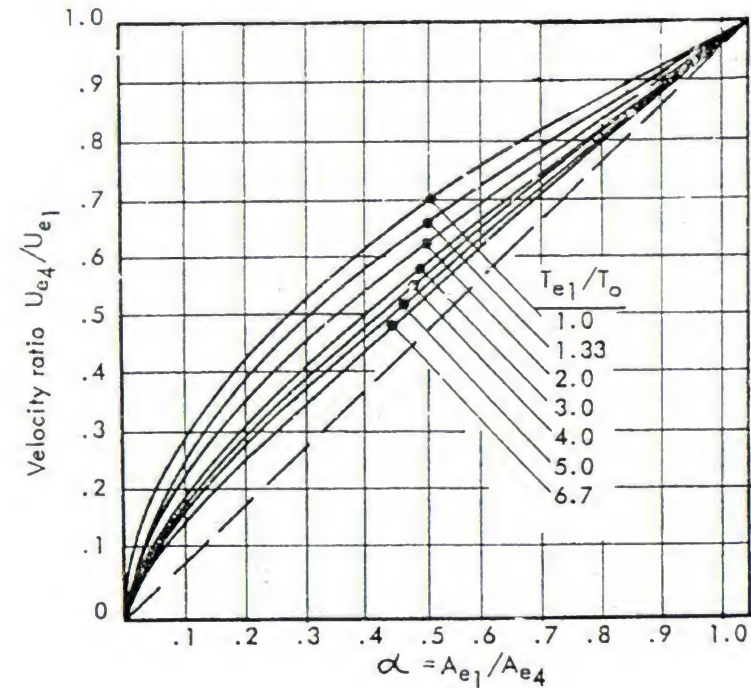
$$\frac{U_{e4}}{U_{e1}} = \frac{1}{2} \left\{ \alpha(1-\beta) \pm \sqrt{\eta^2(1-\beta)^2 + 4\alpha\beta} \right\}$$

$$\frac{T_{e4}}{T_0} = \frac{U_{e4}T_0}{U_{e4} - \alpha U_{e1}(1-\beta)}$$

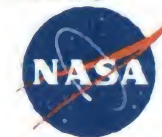
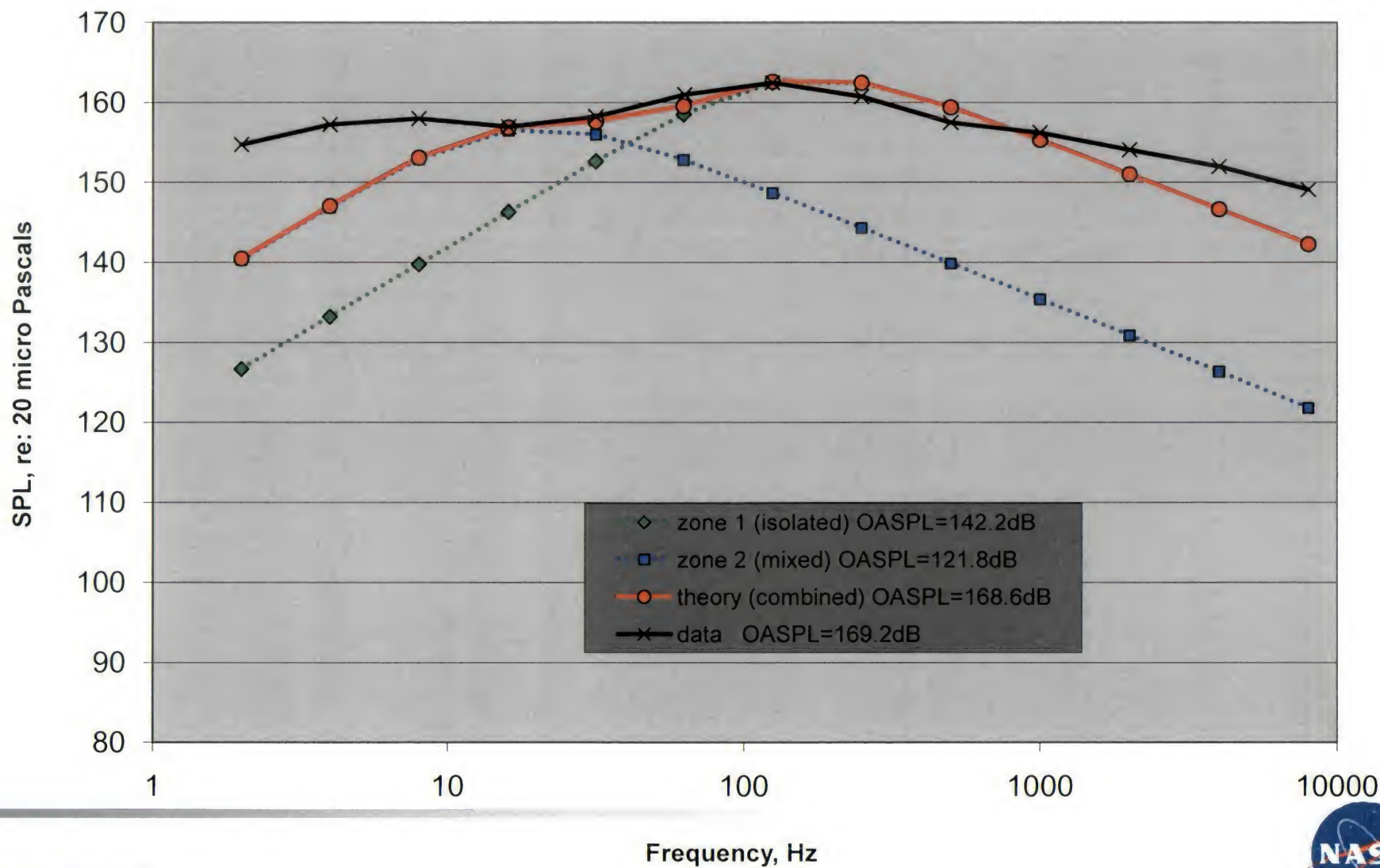
$$\text{where } \alpha = \frac{A_{e1}}{A_{e4}} = \frac{(n^{1/2} - 1)^2}{(r_2/r_{e3} - 1)^2}, \quad \beta = \frac{T_0}{T_{e1}}$$

T_0 = ambient temperature

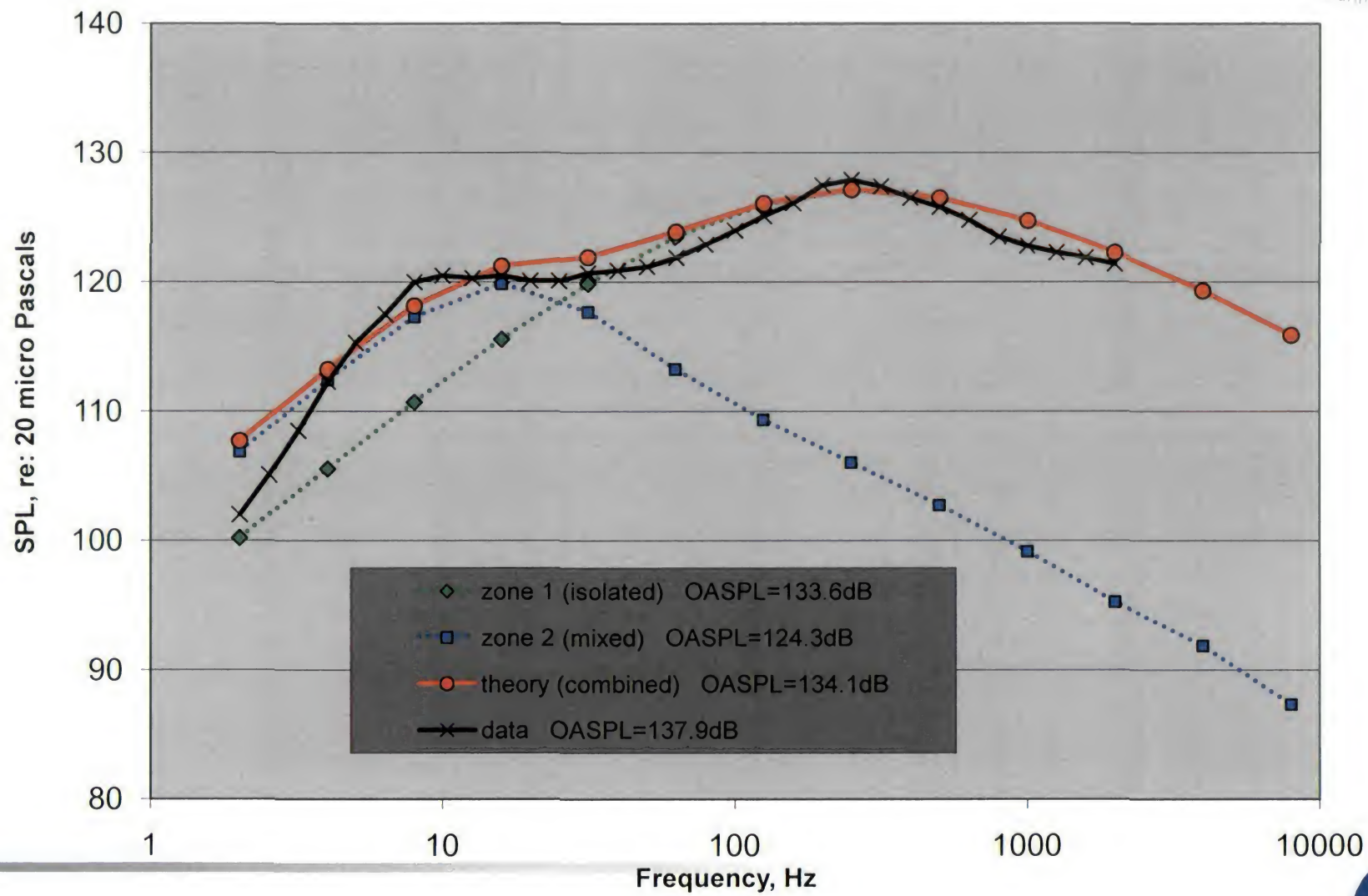
U_{e1}, T_{e1} = individual jet exit conditions



Saturn V



Titan IV



Summary



- PAD is software implementation of launch noise
- Core length, source distribution are moving targets. TEM-13 data validation. More tests are needed
- Drift will require partial flat plate deflection modeling, some geometry extensions in PAD
- Water suppression method was implemented
- Two-zone method was included in PAD to account for clustering effect due to 2 peak frequencies
 - *Isolated zone peak (non-interfering jets)*
 - *Mixed zone peak (considerably lower frequency)*
 - *Eldred' model compares well with the data for clustered nozzles*

